SAFETY EVALUATION OF DELAMINATED CONTAINMENT DOME RE-ENGINEERING

Prabir C. Basu
Civil & Structural Engineering Division, Atomic Energy Regulatory Board, Mumbai India

Vijay N. Gupchup
Formerly Pro-Vice Chancellor, University of Mumbai and Principal & Secretary
VJTI, Mumbai, India

ABSTRACT

Delamination of the inner (primary) containment dome of the Kaiga Atomic power project, Unit-1 occurred during construction. The containment dome delamination was investigated in detail. Subsequent to the investigation of the delamination phenomenon, re-engineering (re-design and re-construction) of the dome was initiated. Methodology for safety evaluation of re-design and re-construction of the IC dome was suitably devised based on the outcome of the investigation work and the same was implemented. Emphasis was laid, during safety evaluation, on the safety of existing ring beam, development of review basis for re-engineered dome, design review and quality assurance in design, quality assurance of materials used, examination of constructibility with the new design, and quality assurance of construction of the re-engineered dome. The inner containment structure was accepted after the successful pre-commissioning proof (structural integrity) and leakage rate tests.

INTRODUCTION

The reactor building of the Kaiga Atomic Power Project, Unit-1 (Kaiga-1) has full double containment with an annular gap of 2.0m between inner (primary) and outer (secondary) containment structures, (fig.1). The inner containment (IC) structure is a prestressed concrete cylindrical shell (42.56 m diameter and 610 mm thickness) capped with a dome having structural configuration of prestressed concrete segmented hemispherical shell (340mm general thickness). It is founded on a reinforced concrete raft of general thickness of 3.5 m. Special feature of this containment dome is that it has four large circular openings of 4.1 m diameter each, for facilitating the erection of steam generators (SG). A ring beam of depth more than 4.0m at the springing level of the dome joins it with the cylindrical inner containment wall (ICW). Prestressing system was designed with post-tensioned 19K13 cables laid in rectangular grid. Two layers of passive reinforcements were provided near the inner and outer surface of the containment dome. No transverse (radial) reinforcement, connecting the top and bottom layers of reinforcement in the dome, and crossties across the ring beam section had been provided.

Delamination of the inner containment (IC) dome of Kaiga-1 occurred on 13th May 1994, during the time of construction [1], after the stressing of 66 prestressing cables out of 183, traversing through the dome. The under surface of the dome in the central portion got delaminated, failed and collapsed completely. Failure surface was mapped and plotted (fig.2). Though the under surface of delaminated dome collapsed, the upper portion remained in position under the action of its self-weight and whatever super imposed load it had on it. The delamination phenomenon and the collapse mechanism were investigated in detail [1], [2], [3].

The delaminated dome was subsequently re-designed and re-constructed. Safety evaluation of the re-engineering of the dome was carried out following a “review basis”, which was developed considering the outcome of the investigation. Present paper deals with the safety evaluation of the re-engineering activities of the delaminated dome.

INVESTIGATION OF CONTAINMENT DOME DELAMINATION

Delamination of Kaiga-1 IC dome was found to have occurred due to the action of radial tension induced by stressing of curved cables. The induced radial tension coupled with the effect of membrane compression was higher than the tensile load carrying capability of the dome in radial direction. Highest radial tension had been observed around the transition zone where the thickness of the dome increased from the normal value of 340 mm to 1100 mm around SG openings. The induced stresses were also higher than the crack resistance capability of the concrete, and for which no radial reinforcement was provided. This was identified as the direct cause of delamination. Delamination originated from the edge of the thickened portion around SG opening and propagated towards crown of the dome. Collapse of under surface of the dome occurred due to the combined effect of progressive extension of lamination cracking and failure of the laminated bottom surface under the action of bending moment induced by the radial component prestressing force.

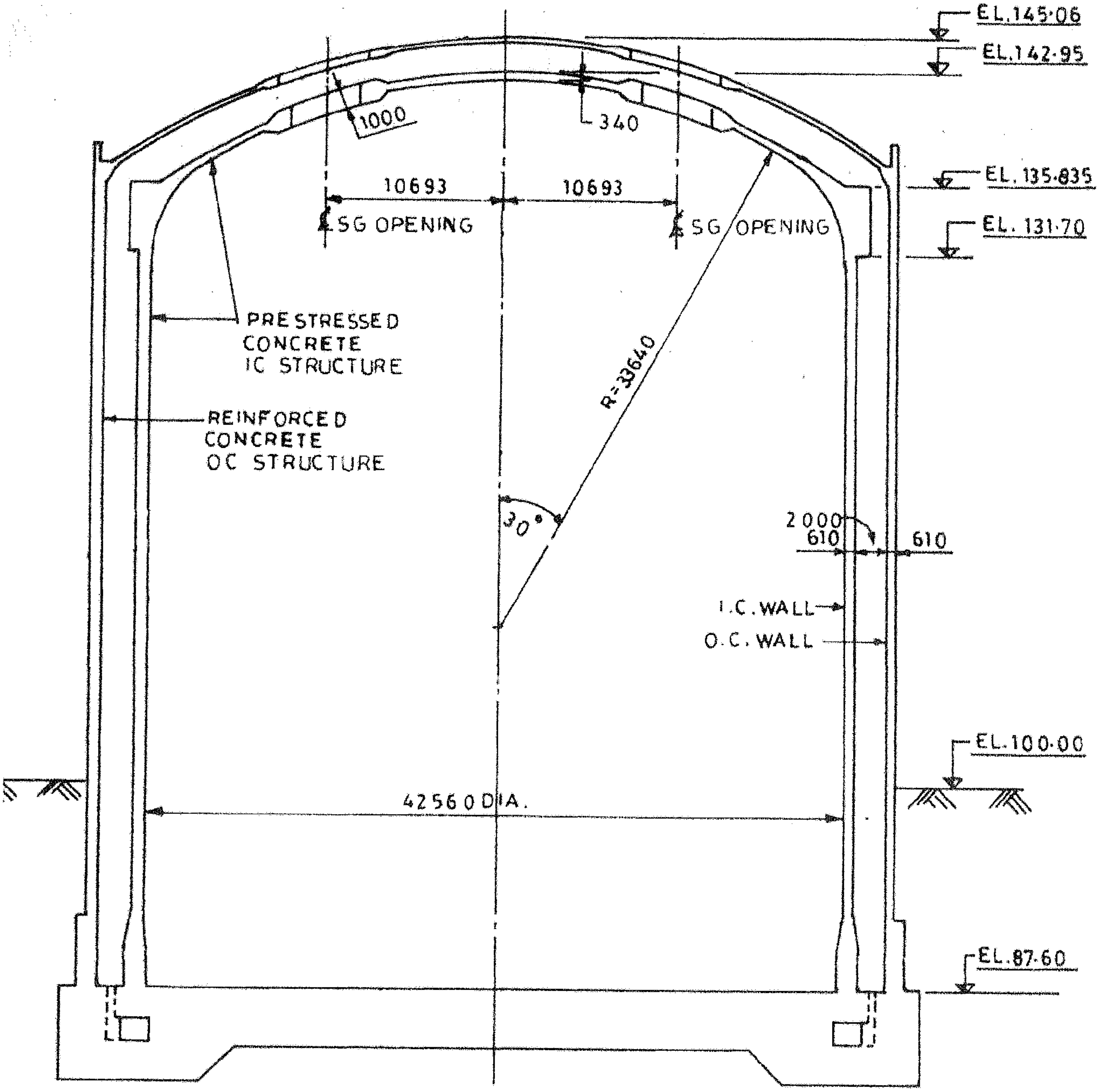

Fig. 1 Structural configuration of Kaiga 1 containment structure.

A number of recommendations had been made for re-engineering of the delaminated dome[1]. Some of the major recommendations were,

1) The intact portion of the dome to be demolished; decision regarding demolition of ring beam or otherwise to be taken following a detailed examination of the beam.
2) Measures to be taken to minimize the induced radial tension in the transition zone, to maintain induced stresses within design allowable, to introduce radial reinforcement, to avoid congestion, to take care of the constraints imposed in the design due to the construction practice adopted.
3) Parallel checking or proof checking of all design output including drawings and detailing to be carried out by independent peer consultants or done independently in-house by the utility.

4) Implementation of appropriate quality assurance (QA) programme in design and construction.
In addition a wide range of recommendations were made regarding various aspects related to design, construction, materials to be used and construction activities, etc.

SAFETY EVALUATION OF CONTAINMENT DOME RE-ENGINEERING

Subsequent to the detailed investigation of the delamination phenomenon, a process of re-engineering (re-design and re-construction) of the dome was initiated. Safety evaluation of the re-engineered dome was carried out based on the outcome of the investigation [4]. Emphasis was laid on the following aspects during the safety evaluation of the re-engineering activities,

- Safety of ring beam;
- Development of review basis for re-engineered dome;
- Design review and quality assurance in design;
- Quality assurance of materials used;
- Examination of constructibility with the new design;
- Quality assurance of construction of the re-engineered dome.

Safety of Ring Beam

Apprehension regarding adequacy of the existing ring beam was expressed because of the following reasons,

1) Observation of cracks on the ring beam surface, especially near the anchorages;
2) Non provision of cross-ties across the ring beam section;
3) Possible impact of sudden cable detensioning, during the course of delamination, on the concrete mass inside the ring beam.

A detailed investigation of the ring beam using non-destructive test (NDT) with 'pulse echo technique' was carried out to assess whether any cracks were induced in the ring beam during the process of delamination. The NDT results suggested that there was very low probability of such cracks in the ring beam [5]. Analytical results also did not indicate possibility of existence of unusual structural cracks inside the ring beam [6]. Based on these observations, the decision of its retention was taken.

The intact portion of the dome, standing in position after delamination, was totally dismantled. Adequate precautions were taken to avoid possible damage to the ring beam during dismantling of the dome. All major cracks on the ring beam were selectively grouted prior to starting the construction of the dome. The ring beam was externally prestressed to strengthen it in view of the non-provision of the cross-ties across the section. In addition, requirement of in-service structural monitoring of the ring beam was stipulated and a detailed procedure was prepared for this purpose.

Review Basis for Re-engineered Dome

The re-engineered dome was designed using the French Code, RCC-G [7]. It does not specify any explicit design criteria for the design of a prestressed concrete containment dome against radial tension while developing the review basis[4] all the unique features of the dome were considered. It basically endorsed the provisions of RCC-G code and in addition, incorporated certain explicit design review, such as design against radial tension. Review basis for the design of prestressed concrete dome without metallic liner against radial tension was prescribed which included the following,

1) The inner containment structure (especially the dome) shall be designed for the total radial tension considering all the phenomena leading to development of such stresses; in particular,
   - Normal radial stress generated due to stressing of curved cable.
   - Radial stress arising out of the effect of change in shell thickness around opening, etc.
   - Radial stress induced due to the presence of hollows (for cable sheaths) within the inplane compressive stress field.
2) Global analysis should be performed to determine stresses and deflections considering all relevant load (actions) and load combinations. Local detailed analysis shall be carried out to determine stresses in the critical areas (such as regions where meridional stress is maximum, geometrical discontinuity is located, zones having closely spaced cables, zones having SG openings, etc) based on the results of global analysis. The effect of the loss in concrete cross sectional area due to cable sheath hollows, indentations, conduits, etc. should be suitably incorporated in the analysis.
3) If the induced radial tensile stress, σ_{tr} (excluding the radial stress due to the effect of the presence of hollows) on the effective area of concrete ligament is more than 67% of the split tensile strength, the concrete section of dome should be re-designed.
   (Concrete ligament is the concrete element of the dome passing through the pocket formed by the cable sheaths laid in rectangular grid arrangement at the mid-section region of the dome. The concrete ligament connects the two

continuous concrete layers of the dome separated by the grid formed by the cable sheaths. The effective area (A_{le}) of concrete ligament is obtained considering the clear distance between two consecutive hollows of cable sheaths on the central plane of the hollows.)

4) If the induced radial tensile stress σ_{tr}, is within 67% of split tensile strength, the transverse reinforcements shall be designed satisfying the following:

a) The induced radial stress (σ_{tr}) in the dome shall not be more than the limiting value of direct tensile stress (σ_{td}). In the absence of detailed methodology, following expression may be considered to calculate σ_{td}.

$$\sigma_{td} = 0.67\, f_{tj}\,(1 - \sigma_c / f_c) \tag{1}$$

Where,

$$f_{tj} = 0.6 + 0.06\, f_{cj} \tag{2}$$

f_c = cracking stress of concrete under compression.
= $0.67 f_{cj}$
σ_c = compressive membrane stress in concrete.
j = age of the concrete: 28 days.

The checking for induced radial stress (σ_{tr}), as stated above, be carried out for following two cases;
Case - 1: Considering σ_c as maximum membrane compressive stress (uniaxial) in concrete.
Case - 2: Considering σ_c as maximum membrane principal compressive stress in concrete (considering biaxial state of stress); in this case the value of f_c is to be increased by 20%.

b) Transverse reinforcement shall be provided for full radial tension including the effect of stress concentration near the cable sheath hollows under the action of biaxial state of membrane stress (only tensile part of the stress concentration effect is to be taken in to account without considering the compression part appearing in the concrete ligaments between the cable ducts) and taking allowable direct tensile stress for steel to be not more than 146MPa for Fe415 grade steel.

5) Radial tension induced due to the presence of hollows within the in-plane compressive stress field may not be considered in designing the radial reinforcement when spacing of prestressing cables are more than three times the diameter of cable sheath. In such case, as a safe practice, stressing of cables and grouting operation of stressed cables be carried out with minimum time gap. Distance between two consecutive ungrouted stressed cables should not be more than twice the spacing of cables.

Design Review

Design review was carried out in two stages. First, the design bases [8] were reviewed with reference to the "review basis". The detailed design was subsequently scrutinized following the accepted design bases. During the design review, care was taken to ensure the resolution of the issues brought out during investigation. Incorporation of all recommendations in the new design was also checked. The design QA documents were reviewed. Detail review of the design documents was done by independent consultant [9]. Utility had also undertaken in-house proof checking of some of the design work done by their consultants [10], [11]. Finally, regulatory review of the independent proof consultant's report and utility's in-house proof checking report were carried out to assess the appropriateness before granting "consent".

Quality Assurance of Material Used

An important special feature of the re-engineered dome was the use high performance concrete (HPC) in the construction [12]. There was limited experience on construction of concrete containment structures with HPC. HPC mix for the re-engineered Kaiga-1 containment dome was developed conducting a series of trial mixes [13]. Quality assurance of the material used was achieved by implementing strict quality control and conducting a number of field trials [13], [14]. Acceptance criteria of concrete specified in RCC-G were adopted for the HPC mix.

In addition to the normal tests for quality control of ingredients of concrete, reinforcement prestressing cables, anchorages, sheaths and other materials following tests were stipulated and carried out,

i) Test to demonstrate that HPC mix had required tensile strength, which was a design parameter,
ii) Independent batch tests of mechanical/time dependent properties of prestressing cables as well as anchorage efficiency and load transfer,
iii) Test to monitor chloride content in the concrete mix taking samples from the batching plant.

Examination of Constructibility with the New Design

A number of mock-up studies were undertaken to examine the constructibility with the new design [15], [16]. These were carried out particularly to examine,

1) Slump retention and pumpability of HPC mix,
2) Placement, spread and compaction of concrete, especially in congested areas,
3) Appropriate green cutting preparation of construction joints for accepting subsequent fresh concrete,

Safety Review of Construction Activities

For implementation of Quality Assurance aspects in the construction and to monitor that the design intent was properly implemented, certain steps were taken. Check lists were specified to ensure proper construction of the structure with HPC. The re-engineered dome was constructed with existing ring beam. Special care was taken to engineer the junction of new HPC of the dome with the old concrete (M35 grade normal strength concrete) of the ring beam to achieve leak-tightness by,

i) appropriate surface preparation prior to concreting,
ii) special type of grouting after construction of the new dome.

A Task Force was constituted to monitor these aspects and a number of inspections were conducted at the project site to help in the safety evaluation during the construction of the re-engineered dome.

ACCEPTANCE OF RE-ENGINEERED CONTAINMENT DOME

The containment dome has been successfully re-engineered and constructed. A number of changes were made in the original design based on the outcome of the investigation and safety evaluation of the re-engineered design. Major changes made in the design were,

1) Increase of general thickness of dome from 340 mm to 470 mm;
2) Increase in minimum cable spacing from 108 mm to 225 mm;
3) Reinforcement layout in orthogonal grid all over the dome with higher spacing;
4) Provision of radial reinforcements;
5) Increase in the slope of transition zone from a slope of 1:1 to 1:3; (to reduce the magnitude of radial stresses)
6) Use of M60 grade high performance concrete in place of M45 grade normal strength concrete; and
7) External prestressing of the ring beam (to take care the possible weakness due to non-provision of cross-ties across the ring beam section).

Final design considerations of the re-engineered dome have been outlined in reference-17. The inner containment structure was tested for the pre-commissioning proof test (structural integrity test) and leakage rate test successfully.

CONCLUSION

Subsequent to the incident of delamination of Kaiga-1 IC dome, a thorough and detailed investigation of the causes of this phenomenon was undertaken. A scheme for reengineering and reconstruction of the dome was proposed. Methodology for safety evaluation of re-engineering and reconstruction of the IC dome was suitably devised based on the outcome of the investigation work and the same was implemented.

The type of structural configuration of the dome, with a doubly curved prestressed concrete shell (segmented hemispherical shell) with four large openings in it, is perhaps the first of its kind for containment. The construction of such a structure with HPC is also an involved process. Several new and innovative methods and techniques have been adopted for the safety evaluation of the re-engineering activities.

The re-engineered containment structure was accepted after successful proof (structural integrity) and leakage rate tests.

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